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DRYING HARDWOODS WITH IMPINGING JETS

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Attempts to develop a more efficient way to dry lumber than conventional kiln-drying have led to recent developments in wood drying technology throughout the world. Spurred on by the rising cost of energy and reduced availability of some of the more popular species, the wood industry has tried to conserve energy and reduce degrade during the drying of wood.

Recently, several nonconventional lumber dryers and drying processes have been operated commercially. For example, a continuous kiln that dries radiata pine studs at temperatures to 300°F was developed by the Australian Commonwealth Scientific and Industrial Research Organization (Anonymous 1975). The dehumidification-refrigeration drying method, developed in Europe and modified with auxiliary heating and steam spray, has been gaining acceptance for drying refractory hardwoods in the United States (Wolfe 1977). Finally, the continually rising temperature or CRT process, involving the maintenance of a nearly constant rate of drying by continuously increasing the temperature in a kiln until completion of drying, has been adopted by many kiln operators throughout North America (Dedrick 1973).

The large capital investment by industry in several countries throughout the world to implement new drying techniques has encouraged researchers at Carbondale, Illinois, to examine other ways to dry wood more effectively. We felt that jet impingement of air on the surface of the wood to increase dryer efficiencies and reduce drying time was worth investigating. This drying method has several advantages over more exotic processes for drying. Since veneers have been dried commercially by jet-drying for over a decade, much of the technology for this type of drying is already available. Also, a jet dryer can be built to accommodate several alternative energy sources (fuel oil, gas, or steam) unlike, for instance, dielectric heating, which requires electricity exclusively.

HIGH TEMPERATURES AND IMPINGING JETS

High temperature drying refers to drying wood above 212°F in the presence of moist air generally at atmospheric pressure, although vacuum or high pressures can be used. The limits of temperature in commercial high temperature lumber kilns have been around 250°F for hardwoods and 280°F for softwoods. High temperature drying of softwoods has met with more success than hardwoods, because many softwoods (which are more permeable and uniformly structured than hardwoods) are easier to dry and the surface quality of softwood lumber is not always as important as that for hardwood lumber. High temperature drying cuts drying time considerably when compared to conventional kiln-drying, but greater susceptibility of the wood to surface darkening, warpage, checking, collapse, and casehardening has discouraged the wood industry from using this method (Wengert 1972).

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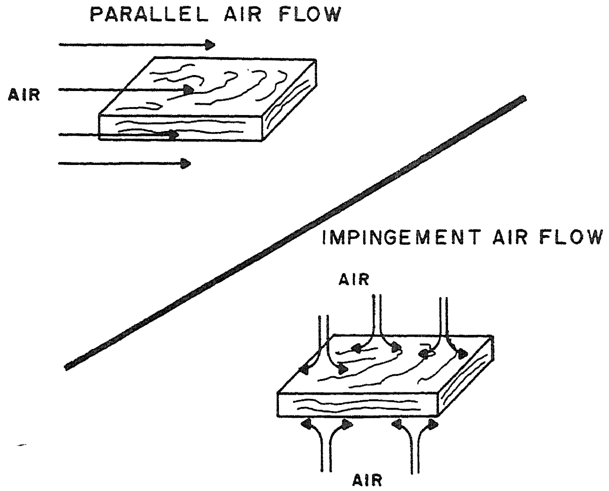

Figure 1.— *Direction of flow relative to the board surface for impingement and parallel air flow.*

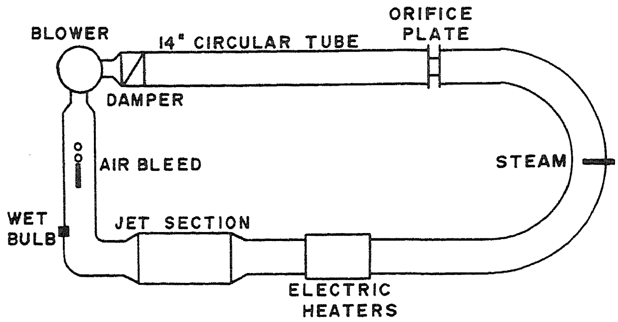

Figure 2.— *Layout of major components of jet dryer system.*

cause of these difficulties, the jet-drying of lumber greater than ½-inch stock has not been reported in the literature. Two previous studies examined the jet-drying of thick southern pine veneers in commercial dryers. Koch (1964) was able to dry $^7/_{16}$-inch-thick veneer at 300°F and 3,500 fpm air velocity in one hour. Similarly, Kimball (1968) dried ⅜-inch veneer at 300°F and 4,000 fpm air velocity in 53 minutes.

PROTOTYPE DRYER

A brief description follows of the prototype jet impingement dryer, capable of handling lumber to a maximum size of 4 inches thick by 12 inches wide by 30 inches long at temperatures from 80 to 400°F and air velocities through the jet from 1,000 to 9,000 fpm. Details are discussed by Rosen (1977).

The dryer is a closed loop recirculating system comprising an industrial centrifugal blower capable of providing 1,800 cfm of air at 15 inches static pressure, a 10 kw open coil duct heater, and a jet section where plenums direct the hot, moist air through two boxes containing opposing bans of $^3/_{16}$-inch jet holes (fig. 2). The ducts are made of 20-gauge galvanized steel, 14 inches in diameter. Temperature is automatically controlled to ± 2°F, and humidity is automatically controlled to a wet bulb of ± 2°F by either venting air if the wet bulb is high or adding steam if the wet bulb is low. Air flow rates are measured from an inline orifice plate and adjustments to air flow are made with a damper on the outlet of the blower.

Wood ready for drying is placed in a restraining rack, which tightly holds the wood on the sides and ends to reduce warp. The wood is loaded through the top of the jet section onto a carriage which reciprocates the boards between the opposing banks of jet holes in 6-inch strokes at 1.33 fpm, so that air is directed equally on opposite lumber surfaces. Movement of the wood relative to the jet holes is necessary for directing the hot air jets to different portions of the wood.

INFLUENCE OF OPERATING VARIABLES ON DRYING TIMES AND WOOD QUALITY

The first step towards development of drying schedules for the jet dryer was to establish relations between drying times and several of the operating variables of the jet dryer. Drying temperature, air velocity (through the jets), and relative humidity (or wet bulb temperature) were thought to have the greatest influence on drying rates. Two popular and permeable species, silver maple (*Acer saccharinum*) and yellow-poplar (*Liriodendron tulipifera*) were dried green from the saw over a range of conditions to establish these relations.

Each run consisted of two boards, 30 inches long, 6 inches wide, and $1^1/_{16}$ inches thick ($^4/_4$-inch thickness). Silver maple boards $2^1/_8$ inches thick ($^8/_4$-inch thickness) were also run. The boards were not end-coated. Silver maple boards were dried over a range of temperatures from 225 to 400°F and air velocities from 1,000 to 9,000 fpm at a fixed wet bulb temperature of 180°F. Yellow-poplar boards were run over a

range of dry bulb temperatures from 225 to 350°F and wet bulb temperatures from 130 to 210°F at a fixed air velocity of 3,000 fpm. Weights were taken at intervals over the drying period to establish drying curves. Drying was terminated when the boards reached about 6 percent moisture content, as estimated by assuming the boards were the same moisture content as thin sections removed from the ends of the board. Boards were conditioned for 1½ hours for $^4/_4$-inch thickness and 3 hours for $^8/_4$-inch thickness at 200°F dry bulb and 190°F wet bulb temperature to relieve stresses and reduce moisture gradients in the wood. Six boards were dried for each condition for $^4/_4$-inch lumber and four boards for the $^8/_4$-inch lumber.

The time required for the wood to be jet-dried to 8 percent moisture content (hereafter referred to as the drying time) was chosen as a basis for comparison of different drying conditions. The drying time was determined for each board from plots of moisture content versus time in the dryer and an average calculated for the four to six boards dried at each condition. Comparisons were somewhat complicated by variations in initial moisture content of 83 to 97 percent in silver maple and 89 to 119 percent in yellow-poplar, as well as variations in the amount of heartwood and sapwood in the boards, especially in yellow-poplar.

The following were found to be true of the influence of temperature and air velocity on drying time. The trends were the same for wood thickness and operating conditions not shown in the figures.

1. Drying time decreased as temperature increased, but the relative decreases above 300°F were small (fig. 3).
2. Drying times were not significantly decreased by increasing air velocity above 3,000 fpm (fig. 4).

Drying times for yellow-poplar were not affected by change in wet bulb temperature for dry bulb temperatures from 250 to 350°F. Similar results were found by Schneider (1972) when pine and beechwood were dried at high temperatures. Although variation in wet bulb temperatures did not influence drying rates, high wet bulb temperatures were best in the dryer to maintain the quality of the dried lumber. When wood is being dried by high temperature jet, the possibility of degrade as a result of overdrying is much greater than when drying at conditions in a conventional kiln. Hardwoods are generally dried no lower than 5 percent moisture content in the United States, before conditioning to a slightly higher moisture content. Thus, to insure no board would go below 5 percent moisture content, the highest temperature

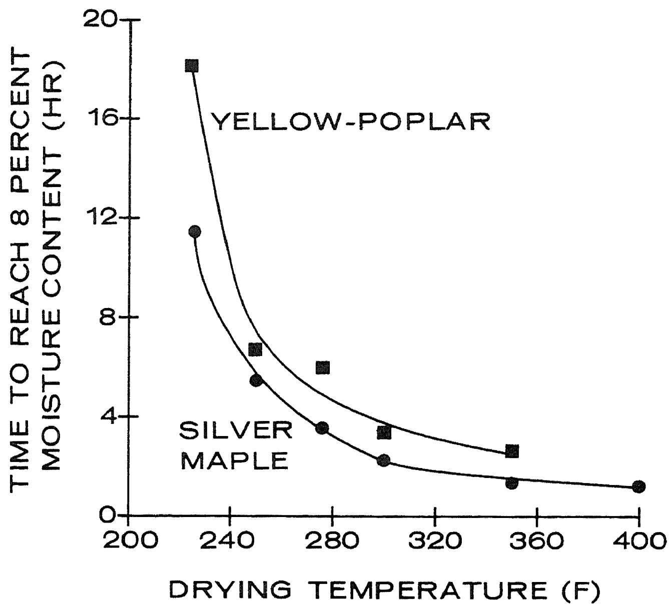

Figure 3.—*Influence of temperature on drying time of $^4/_4$-inch silver maple and yellow-poplar at 3,000 fpm air velocity and 180°F wet bulb. Each point is the average of six boards.*

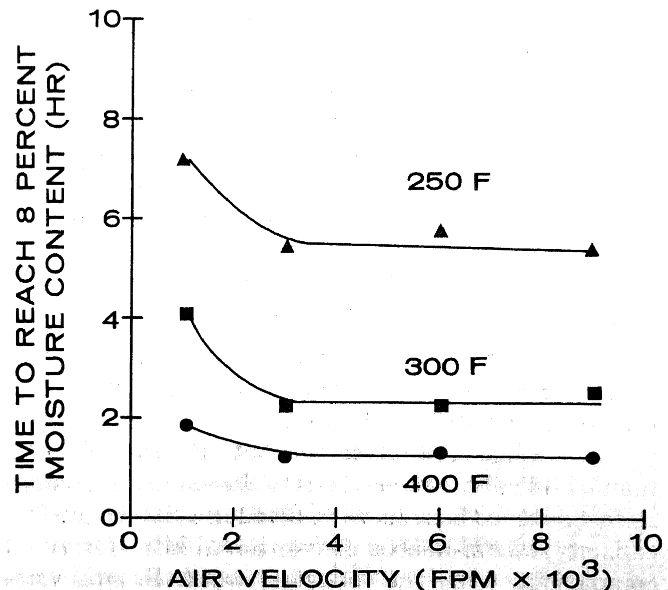

Figure 4.—*Influence of air velocity on drying time of $^4/_4$-inch silver maple at various dry bulb temperatures (180°F wet bulb). Each point is the average of six boards.*

allowable at the end of drying would be 240°F, assuming the dryer could maintain an atmosphere entirely of water vapor (fig. 5).

The problem of localized uneven drying within a board is seen with yellow-poplar. Since yellow-poplar sapwood dries considerably faster than the heartwood (fig. 6), overdrying of the sapwood and underdrying of the heartwood can result in degrade of the wood. Careful control of relative humidity can reduce this degrade, as explained later.

Because of the limited number of boards dried in the jet dryer for each condition, quantitative comparisons of defects such as honeycomb, checking, etc. were impractical so only qualitative results are discussed. Surface darkening, honeycomb, and end checking were the most prevalent defects in the jet-dried boards.

The surface of jet-dried wood was darker than the interior and ranged from light tan, when dried at 225°F, to toast brown, when dried at 400°F. The dark surface layer on wood dried below 350°F was less than 0.01 inch thick and planed off when the board was surfaced. Knots and wane dried faster than clear wood and charred at temperatures above 300°F. Severe honeycomb and end checking as observed in $^8/_4$-inch silver maple boards at all operating conditions; thus, green $^8/_4$ silver maple could not be practically jet-dried at high temperatures. Honeycomb was also present in $^4/_4$-inch silver maple, but the defect was mainly confined to the mineral-streaked areas of the wood and severity decreased considerably at drying temperatures of 300°F and below. Surface checking on the borders of the mineral-streaked areas, not observable immediately after drying, occasionally developed after the wood was stored for several weeks. End checking and honeycomb were found in most yellow-poplar boards, but these defects were confined to the heartwood and were not as severe as in the $^8/_4$-inch silver maple boards.

Based on the influence of dry and wet bulb temper- ıd air velocity on drying time and wood qual- ›dules were developed for silver maple, ıplar, and black walnut. Boards of silver d yellow-poplar, cut to the same dimensions ·dried boards, were dried in 1,500 board-foot steam-heated conventional kilns for direct on with the jet-dried wood. Boards were 3 feet high with ¾-inch stickers before standard schedules as recommended by en (1961). All jet- and kiln-dried boards ısured for crook, cup, bow, twist, and volu- hrinkage and examined for honeycomb,

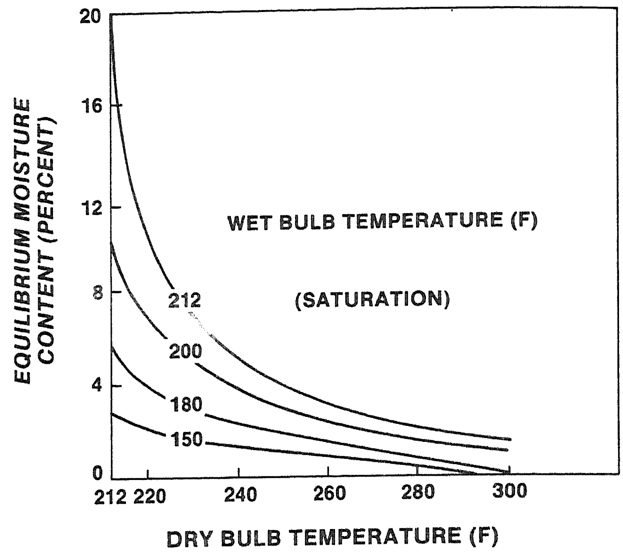

Figure 5.— *High temperature equilibrium moisture content of air-water vapor mixtures at atmospheric pressure (Kauman 1956). The saturation curve at 212°F wet bulb is the maximum equilibrium moisture content obtainable at a given dry bulb temperature.*

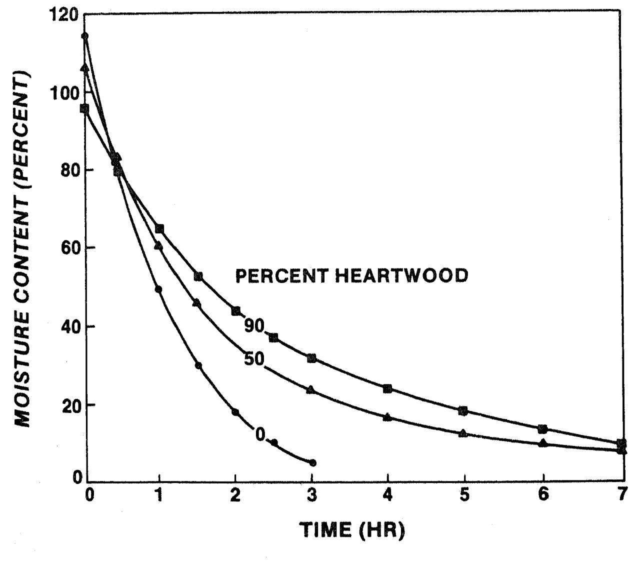

Figure 6.— *Typical drying curves of $^4/_4$-inch yellow-poplar at 300°F (200°F wet bulb and 3,000 fpm air velocity), showing the influence of heartwood content of the wood on drying rate.*

checking, and collapse. Shell and core moisture content, as well as casehardening, was determined for half of the jet-dried boards and three boards from each kiln load.

SILVER MAPLE SCHEDULE

The schedule chosen to jet dry $^4/_4$-inch silver maple was the severest practical schedule in the jet dryer: 300°F dry bulb temperature and 3,000 fpm air velocity. Wood dries 36 times faster under these conditions than it does in a conventional kiln (tables 1 and 2). With the exception of twist, which was better for jet-dried wood, warpage was comparable (not statistically different at the 95 percent level) for both jet-and kiln-dried wood. Volumetric shrinkage was reduced; thus, high temperature drying provided some dimensional stability to the wood. Casehardening was slight in both jet- and kiln-dried wood. Shell-to-core moisture content, not evaluated in kiln-dried wood because of eqipment malfunction, showed only a 2 percent difference in jet-dried wood.

YELLOW-POPLAR SCHEDULE

Since the heartwood of yellow-poplar dries slower and is more subject to drying defects than the sapwood, severity of the drying conditions is controlled by the heartwood. We tried a two-step high temperature schedule to produce acceptable and rapidly dried yellow-poplar. The first step was at a temperature of 350°F for one hour to drive off most of the free moisture from the wood (table 3). Rapid removal of the water kept interior board temperatures well below 350°F. Conditions were then changed to 220°F dry bulb and 195°F wet bulb for 18 hours of drying. Because equilibrium moisture content (EMC) of the wood was 5.5 percent at the latter conditions, the wood could not go below this moisture content. As drying pogressed, the sapwood dried to around 5.5 percent moistue content and remained at this moisture content as the slower drying heartwood approached 6 percent moisture content. As sapwood percentage decreased, the amount of moisture loss after the 350°F drying step decreased. At the end of the drying period, the sapwood board was at the EMC, whereas the boards with heartwood were slightly higher. The difference in moistue content among the three boards was further reduced after conditioning.

Table 1.—*Conventional kiln and jet dryer schedules for drying $^4/_4$-inch silver maple and yellow-poplar*

Species	Dryer time	Dry bulb temperature	Wet bulb temperature	Moisture content
CONVENTIONAL KILN[1]				
	Hours	---°F---	---°F---	*Percent*
Silver				79
maple	0-45	130	123	50
	45-52	130	120	43
	52-72	130	115	30
	72-84	140	100	23
	84-94	150	100	17
	94-104	160	110	12
	104-126	180	130	5
	126-141	160	145	7
Yellow-				102
poplar	0-94	150	143	38
	94-114	150	140	26
	114-119	160	120	22
	119-125	160	110	18
	125-137	170	120	12
	137-161	180	130	6
	161-185	160	145	8
JET DRYER[2]				
Silver				83
maple	0-2.4	300	180	6
	2.4-3.9	200	190	8
Yellow-				92
poplar	0-1	350	180	35
	1-19	220	195	8
	19-24	200	190	9

[1]Rasmussen (1961).
[2]Air velocity, 3,000 fpm.

Table 2.—*Comparison of properties of kiln- and jet-dried 4/4-inch silver maple and yellow-poplar*[1]

Property	Silver maple Conventional kiln	Silver maple Jet dryer	Yellow-poplar Conventional kiln	Yellow-poplar Jet dryer
Moisture content		*Percent*		
Green	79	85	102	92
Dry	7	8	8	9
Shell	—	7	7	7
Core	—	9	7	8
Dry warpage		*Inches*		
Twist	0.22	0.06	0.09	0.14
Bow	0.10	0.17	0.05	0.06
Crook	0.08	0.14	0.03	0.06
Cup	0.10	0.07	0.07	0.07
Volumetric shrinkage		*Percent*		
	10.9	7.6	12.1	9.6
Boards		*Number*		
	70	6	85	20

[1]As per schedules described in table 1.

Table 3.—*Influence of heartwood/sapwood of 4/4-inch yellow-poplar on drying rate of boards jet-dried in two high temperature steps*

Time (hours)	Dry bulb temperature	Wet bulb temperature	EMC	Sapwood (percent) 100	80	50
				Moisture content		
	------°F ------		--------*Percent*--------			
0	—	—	—	91.7	84.4	86.8
0-1	350	180	0	29.8	30.1	38.4
1-19	220	195	5.5	5.6	8.2	9.8
19-24	200	190	10.8	7.3	9.5	9.8

BLACK WALNUT SCHEDULE

Limited work was done on jet-drying the refractory wood, black walnut (Juglans nigra). Attempts at high temperature jet-drying 4/4-inch black walnut were unsuccessful because of severe honeycomb and collapse in the dried boards. We tried a combined low and high temperature schedule plotted in figure 7.

The surface of the wood was kept moist by maintaining the wet bulb temperature just a few degrees below the dry bulb temperature until the wood moisture content dropped below 30 percent. Moisture gradients and internal stresses were thus kept at a level that did not degrade the wood.

Twelve boards of 4/4-inch black walnut heartwood, 30 inches long by 6 inches wide and end-coated with asphalt mastic, were jet-dried according to the schedule in figure 7. Boards were dried from approximately 60 to 6 percent moisture content in 60 hours and then conditioned for 12 hours to 7 percent moisture content. Volmetric shrinkage was 11 percent and shell-to-core moisture contents differed by only one percent. The quality of the wood was good; checking and honeycomb was slight and limited to 2 inches from the ends of the boards. Casehardening was slight and might have been eliminated by a longer period of conditioning.

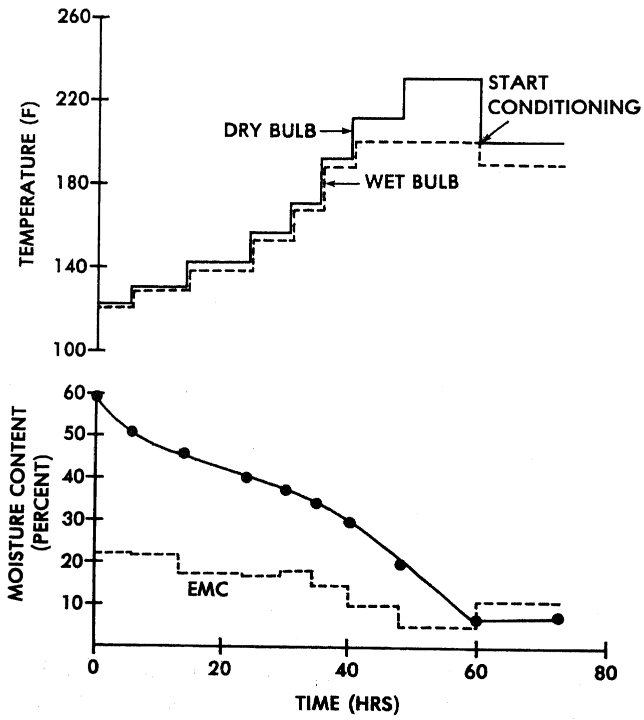

Figure 7.— *Drying schedule and moisture contents for jet-dried 4/4-inch black walnut. The top graph shows dry bulb (solid line) and wet bulb (dotted line) temperatures versus time. The bottom graph shows the moisture content (solid line— each point is an average of two boards) and the EMC (dotted line) associated with the dry and wet bulb temperatures of the top graph.*

SUMMARY

Four-quarter-inch silver maple and yellow-poplar were jet-dried at high temperature in a fraction of the time required in a conventional kiln. The jet dryer also dried $^4/_4$-inch black walnut in 72 hours. The quality of the jet-dried wood was good. A complete evaluation of wood quality should be done on full size lumber, but these promising results should encourage further work on jet-drying of lumber.

An important point brought out by this study is the necessity of maintaining high relative humidities during high temperature drying. Although high temperatures result in faster drying, the wood can become seriously overdried, producing excessive degrade if high humidities are not maintained at the end of the drying schedules. To illustrate this point, assume the conditions in a kiln are 225°F dry bulb and 150°F wet bulb. The EMC, or lowest moisture content to which the wood can be dried, is less than 2 percent (fig. 5) and overdrying of the wood can occur. By increasing the wet bulb to 200°F, the EMC is increased to 6 percent and overdrying of the wood is prevented. Unfortunately, batch kilns and continuous dryers, such as veneer dryers, are rarely capable of maintaining wet bulb temperatures above 180°F (Corder 1976). Kilns capable of achieving wet bulb temperatures of 200°F or better are desirable when woods that require a narrow distribution of moisture content (both among the boards or within individual boards, such as furniture grade lumber) are being dried. High temperature dryers for this lumber must be built tighter and with more insulation than in the past. Direct-fired kilns, in which relative humidity must be kept low to support combustion, are not practical.

Beware of the following problems when woods are being jet-dried at high temperature:

1. Knots that char and loosen.
2. Degrade and excessive surface darkening due to overdrying of the lumber.
3. Degrade in and around wet or dry pockets near stain or rot.
4. Surface darkening.
5. Honeycomb, checks, warp, etc., that are not immediately visible after drying but show up weeks afterward.
6. Excessive degrade in thicker material of a species from which thinner material was successfully high-temperature dried.
7. Highly corrosive environment caused by a combination of high temperatures, high humidities, and organic acids given off by the wood.

Although the challenges to construct and operate a commercial high temperature, continuous, jet-impingement lumber dryer are formidable, we believe the savings in drying time make this process worth considering.

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Silver maple, yellow-poplar, and black walnut lumber was dried in a prototype jet dryer over a range of temperatures from 120° to 400°F and air velocities from 1,000 to 9,000 fpm. Different drying schedules were developed for each type of wood. The quality of the jet-dried lumber was good and compared favorably with kiln-dried lumber.

KEY WORDS: *Liriodendron tulipifera, Acer saccharinum, Juglans nigra,* degrade, high temperature, humidity.